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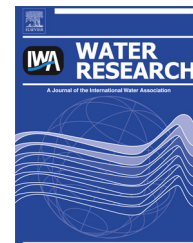




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Stormwater quality performance of a macro-pervious pavement car park installation equipped with channel drain based oil and silt retention devices

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ABSTRACT

This paper reports the results of a two year field monitoring exercise intended to investigate the pollution abatement capabilities of a novel system which offers an alternative to the, now well established, pervious pavement system as a source control device for stormwater management. The aim of this study was to determine the effectiveness of a live installation of a macro-pervious pavement system (MPPS) (operated as a visitors' car park at a prison in Central Scotland) in retaining and treating a range of pollutants which originate from automobile use or become concentrated on the parking surface from the wider environment. The MPPS is a sub-class of pervious pavement system where the vast majority of the surface is impermeable. It directs stormwater into a pervious sub surface storage/attenuation zone through a series of distinct infiltration points fast enough to prevent flooding during the design storm. In the particular system studied here the infiltration points consist of a network of oil/silt separation devices with extensive further pollutant retention/degradation provided during the passage of stormwater through the sub surface zone. Approximately 12 months after the car park was completed a sampling regime was instigated in which grab samples were collected at intervals from each of the three sub catchments whilst, simultaneously, samples were collected directly from the, pollutant retaining, infiltration devices. Through investigation of samples collected at the upstream end of the system, the retention of significant amounts of hydrocarbons and heavy metals in the initial collection devices has been illustrated and the analysis of effluent samples collected at the outlet points indicate that the system is capable of producing effluent which is of a standard comparable to that expected from a traditional pervious pavement system and is acceptable for direct release into a surface water receptor. The system offers the opportunity to accrue the benefits of a pervious pavement when the use of traditional paving surfaces is the preferred option.

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1. Introduction

Most of impervious surfaces in urban areas serve automobile travel, but a significant portion of these, particularly parking areas, driveways, and road shoulders, experience limited traffic loading. Parking areas are typically sized to accommodate peak traffic usage, but it is usually only large parking areas that may be used to full capacity nearly every day (Brattebo and Booth, 2003). Large impervious surfaces commonly lead to multiple impacts on stream systems, including higher peak stream flows, reduction of infiltration which lessens groundwater recharge and increased pollutant loads to streams (Fach and Dierkes, 2011; Freeborn et al. 2012).

Historically stormwater has been considered as a quantity problem to deal with by discharging it directly to water bodies, or treating part of it in wastewater treatment plants (Barbosa et al. 2012). Specific approaches such as strategic/political decisions or source control vs. “end of pipe measures” have influenced the way urban drainage is managed (German et al. 2005), in compliance with more recent legislation requirements (WFD, 2000). It is well known that stormwater transports large quantities of contaminants to receiving waters (e.g., Langeveld et al. 2012; Tixier et al. 2012), thereby being the major contributor to pollution of receiving waters in many countries (Lee et al. 2007). Typical concentration levels of pollutants found in urban retention facilities are summarized in Table 1. The data from Mitchell et al. (2012) show that stormwater monitored in the UK has relatively low suspended

solids compared to global data, whereas the nutrient, toxic metal concentration and oil and grease are within the international range. In terms of biological oxygen demand UK values are slightly under the international values (8.3 and 12.4 mg/l, respectively) while the opposite occurs for the chemical oxygen demand (131.7 and 81.4 mg/l, respectively) (Mitchell et al. 2012). Due to the limited amount of data on the monitoring site characteristics, monitoring set-up and the broad range of concentrations levels, it is impossible to explain the differences recorded in Table 1. The high value of concentrations however, suggests the need for appropriate urban stormwater management strategies.

Many decentralized solutions, normally denominated as “Sustainable Urban Drainage Systems” (SUDS) have been developed and adopted in the UK, and they take into account both the protection of natural resources and future needs (Pratt, 1995; Hvitved-Jacobsen et al. 2010). Permeable pavement systems (PPS) offer one solution to the problem of increased urban runoff and decreased stream water quality associated with automobile usage (Brattebo and Booth, 2003). The upper (wearing) course commonly consists of concrete block pavers which are specially shaped to provide water infiltration channels, which allow stormwater to infiltrate through the surface layer into the sub-base/storage zone. Water is then either infiltrated into the underlying soil or stored for controlled release to a watercourse. Several other surfacing materials are used including both pervious asphalt and pervious poured concrete. Such systems can play a

Table 1 – Concentration levels for principal pollutants in stormwater in urban retention facilities and typical PPS effluents.

		Concentration levels in stormwater (Mitchell et al. 2012) ^a		Concentration levels in stormwater (Fach and Dierkes 2011) ^b	Concentration levels in stormwater (Heal et al. 2009) ^c	Concentration levels in RBS PPS Car park effluents (Schlüter and Jefferies, 2001)	Concentration levels in NATS PPS Car park effluents (Macdonald and Jefferies, 2001)
		Global	UK	Range of median conc.	Mean conc.	Min–Max	Min–Max
pH		–	–	7.3–7.4	–	7.4–8.2	7.6–8.3
TSS	mg/l	138.9	55.2	–	16.8	1–68	9.8–24
NH ₄ –N	mg N/l	0.45	0.55	–	0.08	<0.02–0.57	<0.03–1.13
Tot N	mg/l	2.43	1.93	–	–	1.05–2.92	0.36–1.36
TKN	mg/l	2.08	2.58	–	–	–	–
Tot P	mg P/l	0.35	0.27	–	–	<0.1–0.5	<0.1–0.2
o-Phosphate	mg P/l	–	–	–	–	0.05–0.53	0.01–0.23
Pb	µg/l	154.0	159.4	5	–	9–23	9–24
Zn	µg/l	229.0	185.1	80–115	32	9–32	17–67
Cr	µg/l	15.2	6.8	–	–	<2–4.5	3.8–8.3
Ni	µg/l	25.4	75.4	–	–	0.8–4	1.0–8.7
Cd	µg/l	2.7	2.4	<0.5	–	<d.l.	0.1–5.3
Cu	µg/l	44.2	35.9	5	11	1.7–4.5	5.9–23.1
Petroleum hydrocarbons	mg/l	–	–	–	–	<0.1–3.35	0.15–1.21
Oil and grease	mg/l	4.6	4.9	<0.05–0.26	–	–	–
PAH _{EPA}	µg/l	–	–	<0.01	0.22	–	–

a Average stormwater quality from site mean EMC meta-studies of all land use expect roads.

b The monitoring lasted 20 months, and took place four years after construction of the infiltration facilities.

c Mean values of selected chemical parameters measured in water samples collected along management trains in car parking area by the Environment Agency, 2000–2005.

significant role in mitigating the impacts of stormwater runoff caused by urban development (Pratt, 1995). Whilst traditional PPS offer clear environmental benefits they are not yet universally adopted in new developments, arguably due to unfounded reasons such as fears amongst specifiers that the traditional PPS (e.g., block paved surfaces or porous asphalt) have a reduced longevity or poorer level of performance (e.g., tendency to clog or the need to use specialised surface cleaning processes; Dierkes et al. 2002). Traditional PPS have shown a poor pollution retention performance in response to major accidental oil or fuel releases likely to occur in parking areas (Newman et al. 2004). The use of specialised geotextiles enhances the pollution retention performance of traditional PPS, even these do not have unlimited capacity (Puehmeier and Newman, 2008). Alternative solutions to dealing with accidental oil and fuel spills in parking areas, which is reported as second most frequent type of pollutant in inland waters in the UK (UKGF, 2012), are still needed.

A novel system that benefits from the advantages offered by traditional PPS and yet allows for the use of traditional asphalt (or poured concrete) surfacing has been recently identified by Newman et al. (2011). The macro-pervious pavement system (MPPS, term first coined at the World Environmental and Water Resources Congress, USA, by Newman et al. 2011) is a sub-class of PPS where the vast majority of the surface is impermeable. A form of it was proposed (under a different name) in the 1980s, but without consideration of pollution retention or treatment in the design (Raimbault, 1993). The design of an environmentally sound MPPS should provide an initial treatment process that

removes suspended solids, heavy metals, organic micro-pollutants and nutrients. The MPPS used in this study directs stormwater underground through a collection of distinct infiltration points fast enough to prevent flooding during the design storm. Each infiltration point consists of a network of modified oil separation devices and channel collectors enhanced with a floating mat (Culleton et al. 2005). The channel collectors (different to channel drains) collect water over a short length (longitudinal flow along the channel is not possible), and then the water leaves the collector to discharge into the sub-base or a shallow sub-surface tank. The two oil separation devices used in this study have been tested individually (but not as part of a long-term study on a full scale live system; Puehmeier et al. 2005).

The primary objective of this study was to determine the effectiveness of a live installation of a novel MPPS, operated as a car parking area, in retaining and treating pollutants of concern as compared to data derived from studies on traditionally designed previously paved car parking areas. This information is important in examining long-term performance and operational characteristics of MPPS.

2. Materials and methods

2.1. The study site

The study site was located at the visitors' car park at a prison in Central Scotland (UK). The car park was constructed in 2008 and consisted of a total area of ca. 3000 m² divided into 3 sub

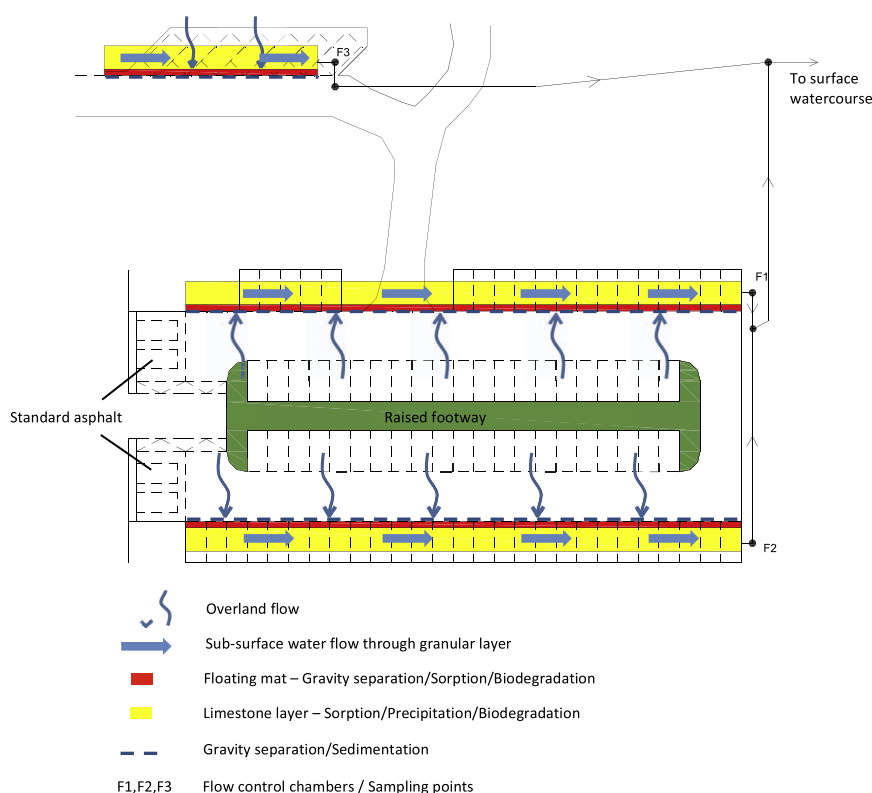


Fig. 1 – Plan showing the schematic layout of the macro-pervious pavement system. (Note: only those parts of the system relevant to this paper are shown).

catchments (i.e., two of around 1350 m² and one of 300 m²) each (Fig. 1). Each sub-catchment was provided with separate flow control chambers downstream of the system (F1, F2 and F3; Fig. 1), to allow flow control through an orifice plate at the outlet and provide convenient sampling points (S14, S15; Fig. 1). The surface of the car park was of impervious asphalt. It should be noted that the installation of the system studied here was carried out without any involvement of the authors; it is therefore understood that the company who installed the system did not take any special precautions in the installation (as opposed to what might have been expected in a demonstration project). Thus, the use of this study site represents a typical installation rather than a best case situation.

2.2. The macro-pervious pavement system

The form of macro-pervious pavement system used in this study had two main components promoting retention and reduction of oil and suspended solids: oil separating collector channels and floating mat interceptors (Fig. 2). A brief description of each one of them follows.

A novel oil separating collector channel co-invented by one of the authors (Shuttleworth et al. 2004) and commercialised by Permavoid Ltd. as *Permachannel* (Warrington, UK) worldwide was the focus of this study. This collector channel was initially designed to retain suspended solids (and the micro-pollutants associated with them) and oil, to prevent the system overwhelming the subsequent pollution prevention mechanisms provided by the system. The collector channel used in this installation constituted a relatively shallow miniature gravity separator. Unlike a traditional linear channel drain, the oil separating collector channels were isolated from one another and served a limited catchment area per unit length; in the installation focus of this study, they were

installed at a maximum rate of 1 m of collector channel per 25 m² of catchment. The volume available in each of these collector channels was ca. 7.5 L, normally occupied by water. This water would be displaced through the gravity separator in the event of a body of oil entering the collector channel, allowing for the system to retain any major hydrocarbon spillage within a limited number of channels. The trapped hydrocarbons can then be easily removed, thus preventing free product oil from reaching the sub-surface attenuation and treatment zone. The performance of the collector channels in these circumstances (particularly when occurring during an intense rain event) has been previously reported (Puehmeier et al. 2005).

A floating mat interceptor originally developed for use in pavements with pervious surfaces (Newman et al. 2004; Puehmeier et al. 2005) was also used in the installation under study, and was placed directly downstream of the outlets from the collector channels, with an interface provided by a flow diffuser to disperse the kinetic energy of the flowing water. The principle of the device is that, within a still water body, droplets of free product hydrocarbons will float to the surface and if they collide with a floating mat of a suitable material they will interact with it and be trapped long enough to allow a biodegradation process to take place. Following interaction with the floating mat interceptor, the water passed into a preliminary storage void provided by load bearing plastic void forming boxes (Permavoid Ltd., Warrington, UK) and the water exited from this section through a geotextile which provided further filtration and oil sorption capacity. Finally, there was a large body of granular stone (nominally 5–40 mm) which served as a storage volume for flow attenuation and as a surface for sorption and degradation of micro-pollutants before controlled release through the flow control chambers mentioned previously.

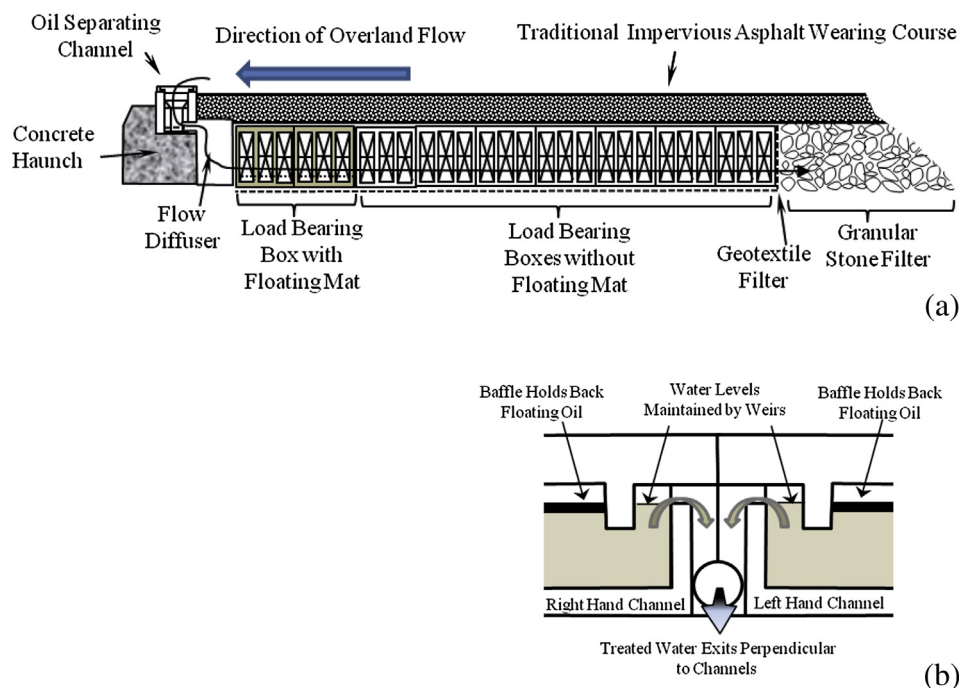


Fig. 2 – The macro-pervious pavement system, (a) side view, (b) front view.

2.3. Sampling protocol

Approximately 12 months after the car park was completed a sampling regime was instigated in which grab samples were collected from each of the three flow control chambers immediately downstream of the treatment system in each sub catchment (manholes F1, F2, F3; Fig. 1). Samples were collected from April 2011 to September 2012. Sampling was not restricted to rainfall events; however, for each sampling event sufficient recent rainfall was available such that the pipes entering at least one of the flow control chambers was actively discharging. Effluent water samples were collected from flowing streams entering into the flow control chambers. When water was not flowing into the chambers at the time of sampling, or where the inlet pipe to the flow chamber was submerged, effluent water samples were collected from the water which was present within the flow control chambers.

At each sampling event a pair of collector channels was selected at random to provide a liquid sample, containing the easily suspendable materials (those collected from the channel after mixing with a paddle mixer). After allowing suspended material to settle for 2 min a “sludge” sample was scooped from the base of the drain.

After collection, samples were placed in amber glass bottles (organic determinands) or new plastic bottles (inorganic determinands), kept in a cooler box with ice, and transported to the laboratory where they were stored at 4 °C prior to analysis within one month (or sooner if demanded by the quality assurance system of the laboratory).

2.4. Physical and chemical analysis

Physical and chemical analysis of the water and solids collected from the site were conducted at Northumbrian Water Scientific Services, NWSS (Newcastle upon Tyne, UK) accredited laboratory (United Kingdom Accreditation Service, UKAS). As such, the quality assurance/quality control (QA/QC) procedures reported here are assessed against internationally agreed standards by an external accreditation body (UKAS) on a regular basis. Before putting the accredited methods into use they were validated by use of certified reference materials (CRMs) or, if suitable CRMs were not available, by using spiked blanks and spiked samples according to the protocols agreed with the accrediting body.

Characterisation of stormwater pollutants included: suspended solids (TSS), heavy metals (lead, zinc, chromium, nickel, cadmium and copper), organic micropollutants (total hydrocarbons, aliphatic hydrocarbons, benzene, toluene, ethyl benzene, xylenes and methyl tertiary butyl ether - MTBE) and nutrients (total oxidised nitrogen, ammonium, total phosphorus and ortho-phosphate). All methods used except for MTBE were within the accreditation schemes of the laboratories performing the analyses. MTBE was determined as an additional parameter within the volatile organic compounds (VOC) suite and QC of the process was achieved by means of spiked blanks.

Total suspended solids (TSS) were determined on the shaken sample by filtration onto a pre-weighed glass fibre filter paper (Whatman GF/C 70 mm) and determined gravimetrically after washing and drying at 105 ± 5 °C (NWSS Method H035). Heavy metals were determined by inductively coupled plasma

mass spectrometry (Agilent 7500 ICP-MS). For metal determination in solids from the channels the dried samples were pre-treated by aqua regia digestion (NWSS Method H198).

VOCs in the water samples were determined by purge and trap concentration followed by capillary gas chromatography (GC) using ion trap mass spectrometry detection (NWSS Method O026). VOCs were determined on solid samples by headspace concentration followed by capillary GC using ion trap mass spectrometry detection (NWSS Method O085). The instruments used were a Varian Saturn 2100T GC–MS with a Tekmar Aquatec headspace sampler or Tekmar Velocity XPT purge and trap sampler, respectively. Separation was achieved using a Restek Rtx-VMS column (20 m \times 0.18 mm \times 1.0 μ m). The temperature program comprised 50 °C for 3 min, 20 °C min^{−1}–200 °C, where it was held for 0.5 min.

Total and aliphatic hydrocarbons were determined on the water samples by extraction into hexane, using NWSS TPH Method O082. A Varian 3400 GC with a Finnigan MATT A200s autosampler or a Shimadzu GC-2010 with an AOC-20i autosampler, both with a flame ionization detector (FID) were used for the analysis. Separation was achieved using a Varian VF-5ht Ultimet™ column (15 m \times 0.32 mm \times 0.1 μ m). The temperature program comprised 45 °C for 0.5 min, 50 °C min^{−1}–360 °C, where it was held for 0.2 min. Total petroleum hydrocarbons were determined in the solids by extraction with acetone/hexane and GC–FID analysis (as above), using NWSS TPH Methods O081. For additional characterization, the total petroleum hydrocarbon (TPH) extract was fractionated using a silica column, and eluted with hexane to obtain the aliphatic fraction.

Total oxidised nitrogen and ammonium were analysed using a continuous flow analyser (SA 3000/5000 CFA with SA 1074 autosampler unit and SA 1530 rinsing valves; Skalar) using NWSS Method H027. Ortho-phosphate was determined with a Kone Analyser, following the standard method ALcontrol Method Number TM184.

pH was determined using an automated method with a Metrohm LL Aquatrode plus combined glass electrode, Metrohm 815 robotic USB sample processor XL and Metrohm 843 pump station. The equipment was calibrated using buffer solutions of known pH, according to QC/QA procedures.

Each quality parameter/pollutant was described by the range of concentrations (maximum, minimum and calculated 95 percentile) and the-unweighted mean concentration over eight events.

3. Results and discussion

The MPPS car parking facilities were monitored from April 2011 to September 2012 and samples were collected periodically. Concentration levels for principal pollutants present in the solids and liquids collected from the flow control channels are shown in Tables 2 and 3, respectively. The characteristics of the effluent collected from manholes F1, F2 and F3 are shown in Table 4.

3.1. Retention of pollutant in the channel drains

Throughout the sampling period none of the investigated channel drains contained a macroscopic body of free oil but all

Table 2 – Concentration of contaminants on the solids collected from the channels (2 channels randomly selected at each sampling event) (n = 8 events).

	Units	Mean	Max	Min	Median	95th percentile
Pb	mg/kg	44	160	16	21	129
Zn	mg/kg	194	340	120	150	331
Cr	mg/kg	25	61	13	19	51
Ni	mg/kg	26	77	13	17	62
Cd	mg/kg	18	72	<0.03	0.3	61
Cu	mg/kg	43	160	16	25	121
Total hydrocarbons	mg/kg	3500	13,000	1100	2100	9710
Aliphatic hydrocarbons	mg/kg	1578	4400	420	1125	3750
Benzene	µg/kg	n.a.	<10	<10	n.a.	n.a
Toluene	µg/kg	17	72	<10	<10	54
Ethyl Benzene	µg/kg	1510	4200	24	1200	3500
Total Xylenes	µg/kg	66	201	<10	17	166

Note: n.a. - not applicable.

contained either a continuous sheen of oil or a collection of isolated droplets (visual observation). All channel drains contained a relatively large amount of non-suspendable matter. No attempt was made to quantify this by completely evacuating the channels but the minimum amount of sample readily available from two adjacent channel drains was always greater than 200 g (dry weight). Mean concentration of total and aliphatic hydrocarbons in the liquids collected from the channels (30.0 and 5.8 mg/l, respectively; Table 3) were relatively higher than the values reported in other car parks in the UK (Table 1). Maximum recorded concentrations of total hydrocarbons were one order of magnitude higher (150 mg/l), which might be typical of accidental spills. In addition, the typical (mean) concentration of oil and grease (mostly aliphatics) in stormwater reported in the UK is 4.9 mg/l, which is similar to the concentration of aliphatic hydrocarbons found in the liquids collected in the channels. Values of heavy metals recorded in the channel drains were overall lower than those typical of stormwaters in the UK.

The concentration of pollutants monitored in the solids collected from the channels was in general high, particularly

for pollutants which would be expected to derive from vehicle parking. The origin of the aromatic volatile organic carbons (VOC – benzene, toluene, ethyl benzene and total xylenes) was assumed to be either loss of fuel or as material adsorbed by the lubricating oil of vehicles in the engine and then lost as oil leaks. While the concentration of these VOCs was very high, it was not established whether these compounds were directly sorbed to the solids or dissolved in free oil which was physically trapped upon the particulate matter.

3.2. Effluent samples

The data for the effluent analyses are shown as summary statistics in Table 4. Values of total hydrocarbons, total suspended solids, heavy metals, nutrients and pH reported in other car parking areas using traditional PPS in the UK are shown in Table 1 for comparative purposes. Specifically, these traditional PPS sited in Edinburgh have been previously described as the NATS car park (Macdonald and Jefferies, 2001) and the Royal Bank of Scotland (RBS) car park (Schlüter and Jefferies, 2001). The data has been extracted to produce

Table 3 – Concentration of contaminants in the liquids collected from the channels (2 channels randomly selected at each sampling event) (n = 8 events).

	Units	Mean	Max	Min	Median	95th percentile
pH		–	8.0	6.7	7.0	–
TSS	mg/l	16,312	66,000	1900	8850	50,250
NH ₄ -N	mg N/l	0.23	0.85	<0.2	<0.2	0.7
TON	mg N/l	0.25	0.58	<0.4	0.2	0.5
TP	mg P/l	11	38	<0.3	6.6	31
Pb	mg/l	1.18	2.7	0.28	1.1	2.5
Zn	mg/l	7	13	2	7.8	12.4
Cr	mg/l	0.19	0.3	0.03	0.22	0.38
Ni	mg/l	1.8	11	0.0007	0.29	7.9
Cd	mg/l	0.012	0.028	<0.0002	0.011	0.026
Cu	mg/l	1.1	2.5	0.22	1	2.29
Total hydrocarbons	mg/l	30	150	1.8	4.7	120
Aliphatic hydrocarbons	mg/l	5.8	29	0.71	0.95	22
Benzene	µg/l	–	<1	<1	–	–
Toluene	µg/l	–	<1	<1	–	–
Ethyl benzene	µg/l	–	53	<1	–	–
Total xylenes	µg/l	–	<2	<2	–	–

Table 4 – Concentration of contaminants in the effluent collected at flow control chambers F1, F2, F3 (Fig. 1) (n = 8 events).

	Units	Mean			Min			Max			Median			95th percentile		
		F1	F2	F3	F1	F2	F3	F1	F2	F3	F1	F2	F3	F1	F2	F3
TSS	mg/l	4.4	5.7	4.8	<3	<3	<3	13.0	12.0	18.0	2.3	4.0	2.8	11.3	11.0	13.5
NH ₄ –N	mg N/l	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
TON	mg N/l	0.74	0.45	0.43	<0.40	<0.40	<0.40	1.30	0.92	0.71	0.69	0.41	0.47	1.27	0.85	0.69
TP	mg P/l	<0.3	<0.3	1.7	<0.3	<0.3	<0.3	<0.3	<0.3	13.0	<0.3	<0.3	<0.3	<0.3	<0.3	8.5
o-Phosphate (n = 2 events)	mg P/l	0.11	0.16	<0.05	0.07	0.06	<0.05	0.14	0.25	0.06	–	–	–	–	–	–
Pb	µg/l	1.1	<2.0	<2.0	1.0	<2.0	<2.0	2.1	<2.0	<2.0	1.0	<2.0	<2.0	1.7	<2.0	<2.0
Zn	µg/l	48.6	12.7	4.7	6.0	<6.0	<6.0	280.0	34.0	9.2	6.0	5.8	<6.0	204.0	33.3	8.5
Cr	µg/l	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	2.1	2.5	5.7	<0.3	<0.3	2.3	<0.3	<0.3	5.4
Ni	µg/l	<0.4	2.5	0.8	<0.4	<0.4	<0.4	2.8	8.4	1.8	<0.4	1.4	0.8	2.2	7.5	1.7
Cd	µg/l	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.3	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Cu	µg/l	17.5	15.3	10.5	<7.0	<7.0	<7.0	43.0	56.0	22.0	10.5	5.6	9.3	39.9	44.8	21.6
Total hydrocarbons	mg/l	0.07	0.18	0.07	0.02	0.02	0.02	0.19	0.35	0.15	0.05	0.18	0.06	0.16	0.35	0.14
Aliphatic hydrocarbons	mg/l	0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.02	0.08	<0.01	0.01	0.01	<0.01	0.02	0.06	<0.01

maximum and minimum data only (and has been converted to match units with those reported here).

The pH is shown in Table 5 in the form of raw data rather than summary statistics. Clearly the pH generally increased as the water passed through the granular region. This probably reflects the fact that the voided subbase is constructed from limestone.

Suspended solids in the effluent from the macro-pervious pavement compared well with the data previously reported for the RBS and NATS pervious pavements (Macdonald and Jefferies, 2001; Schlüter and Jefferies, 2001). An additional series of seven samples was taken from flow chamber 2 (F2) over a period of 8 h during a rain event. The concentration of suspended solids of the majority of the samples was below 3 mg/l (the concentration of one sample was 5 mg/l).

The data for hydrocarbons presented in Table 4 shows a similar pattern. The maximum effluent concentrations are clearly well below those previously reported (Table 1) and certainly significantly below the 5 mg/l limit for a class 1 oil interceptor (British Standards Institution, 2002). Given the very high levels of hydrocarbons reported for both liquid and solid components collected from the channel drains (Tables 2 and 3) the data suggests that a relatively high mass of the hydrocarbons are retained in the easily accessible zone. The results of the retention of hydrocarbons are further supported

by a series of 7 additional samples which were collected from the pipe feeding flow chamber 2 (F2). Results ranged from 0.02 mg/l to 0.05 mg/l with a mean value of 0.03 mg/l. It should be noted that for both, suspended solids and hydrocarbons, the proportion of the pollutants retained in the channels and sub-pavement zones was not determined (and thus, further studies are suggested).

Significant quantities of heavy metals were also present in the channels. In the case of the non-suspendable solids samples, for example the maximum zinc concentration was 340 mg/kg (Table 2) with a concentration in the liquid samples as high as 13 mg/l (Table 3). In the effluent samples, Table 4 shows that the zinc concentration never exceeded 0.28 mg/l. The level of zinc contamination depends on local practices, particularly regarding the use of zinc on roofs, but also street runoff since zinc is a component of certain vehicle parts (tyres and brake pads) (Legret and Pagotto, 1999). As for lead, the concentrations in the solids collected from the channels varied between 16 and 160 mg/kg (median 21 mg/g); concentrations in the liquid collected from the channels were substantially lower, from 0.3 to 2.7 mg/l (median 1.1 mg/l). Presence of lead probably resulted from lead use in brake pads (Legret and Pagotto, 1999), and a small contribution may also result from exhaust emissions (Denier van der Gon and Appelman, 2009). As for copper, concentrations in the solids collected from the channels varied between 43 and 160 mg/kg (median 25 mg/kg); concentrations in the liquid collected from the channels were in the range of 0.2–2.5 mg/l (median 1.0 mg/l). According to Legret and Pagotto (1999) the content of copper in brake pads is 14 g/kg, which was one potential source of copper in the channels. Another potential source of copper in runoff water was from roofing (Wallinder et al. 2009). Similar relative concentrations were observed for all the other metals measured, with cadmium never being detected in the effluent. The concentrations of all heavy metals monitored in the effluent were below derived discharge concentrations limits (Table 6), which were calculated using environmental standards for discharge to surface

Table 5 – pH of effluent samples and liquid collected from channel drains (Fig. 1) (n = 8 events).

	Event							
	1	2	3	4	5	6	7	8
pH in effluent of selected channel	7.5	7.0	7.3	7.9	6.5	6.7	8.0	7.0
pH in chamber 1	9.8	10.2	9.4	9.5	8.8	8.7	9.1	9.6
pH in chamber 2	10.2	9.3	9.6	10.0	9.3	11.1	10.2	9.7
pH in chamber 3	11.2	11.1	10.2	10.6	10.2	6.7	11.0	11.2

Table 6 – Comparison of monitoring and derived discharge concentration limits to assess the effectiveness of MPPS.

	Units	Mean concentration from channels (Table 3)	Max. concentration in effluent (Table 4)	Environmental standards for discharge to surface waters (SEPA, 2010)	Derived discharge concentration limit, annual mean ^I
TSS	mg/l	16,312	18	n.a.	25 ^{IV}
NH ₄ -N	mg N/l	0.23	0	0.021 ^{II}	0.42
TON	mg N/l	0.25	1.30	n.a.	–
TP	mg P/l	11	13 ^{VI}	0.12	2.4
Pb	µg/l	1180	2.1	7.2	144
Zn	µg/l	7000	280	50 ^{III}	1000
Cr	µg/l	190	5.7	3.4	68
Ni	µg/l	1800	8.4	20	400
Cd	µg/l	12	0.3	0.09 ^{III}	1.8
Cu	µg/l	1100	56	10 ^{III}	200
Total hydrocarbons	mg/l	30	0.35	n.a.	5 ^V

Note: ^IA dilution factor 1/20 was assumed; ^{II}; ^{III}For Cu, Zn, Cd, the annual mean values vary dependent on the hardness of the water, Class 3: >50–100 mg CaCO₃/l was assumed; ^{IV}Source: EPA-Ireland (2012); ^VLimit for class 1 receptor (BSI 2002); ^{VI}This was a single unexplained event. All other samples <0.3 mg/l; n.a.-not available.

waters (SEPA, 2010) assuming a dilution factor 1/20, as discharge limits for car park areas are not available.

In terms of the efficacy of the macro-pervious pavement system in removing total oxidised nitrogen and ammonia, ammonia was never detected in the effluent. It should be noted that the laboratory reporting limit for ammonia in this study was higher (0.2 mg N/l) than those in previous studies (0.02 and 0.03 mg N/l, respectively) (Table 1), however in both sets of comparative data, effluent maximum values for ammonia (0.57 and 1.13 mg N/l, respectively) exceeded the reporting limit in the current study. Higher values of total oxidised nitrogen (max) than in the channels (mean) were reported (Table 6), which was probably caused by oxidation of reduced nitrogen within the system.

Table 4 also presents the data for total phosphorus and for ortho-phosphate, which was only specified in sampling events 7 and 8 and thus comparison with the previous data from the pervious pavements was difficult. This was further compounded by the fact that the total P was determined with a reporting limit of 0.3 mg P/l, well above the minimum values previously reported for the comparative car parks (Table 1). A single high value for total P (13 mg P/l), occurred at sampling event 3 from one sampling location only, and remains unexplained. Otherwise the results from the macro-pervious pavement system indicated that despite a maximum concentration of 38 mg P/l being detected in the liquid from the channels (Table 3), the results obtained in the effluent were generally low. It is suggested that the elevated ortho-phosphate result in flow chamber 3 may have been due to the following: (i) a significant amount of contamination passing via the channel drain and sub-surface attenuation zone into the chamber; or (ii) direct entry into the chamber; or (iii) someone pouring waste into it (since the flow chamber covers were not locked). In addition, in this case the flow chamber was sampled at a time when the water level was above the inlet to the chamber and was thus collected from the water body retained in the chamber. The cover to flow chamber 3 was a heavy duty ductile iron cover and was in a position where vehicles park directly on top of it. Inputs of fertilisers from the nearby landscaping areas or rust treatment fluids from the many and varied vehicles on site was a

possibility. Furthermore, deliberate disposal of material into the flow chamber could not be discounted. It is notable that 40 days later when the chamber was again sampled in a static condition the result was again lower than the laboratory's reporting limit (0.3 mg P/l). The limited number of ortho-phosphate determinations also tended to indicate that the performance seemed to be comparable with those from pervious pavement car parks reported in Table 1. Pseudomonads are microorganism that have the ability to solubilize the insoluble phosphates (Naik et al. 2008), and are regularly implicated in the biodegradation of hydrocarbons (Atlas, 1981). Therefore, it is suggested that utilisation of phosphorus by microorganisms within the system is a potential removal mechanism. Chemically mediated mechanisms of removal are also possible, which have been widely reported, e.g., in the fields of wastewater treatment (Berg et al. 2005) and agriculture (von Wandruszka, 2006), showing that both surface reactions and precipitation of P take place, especially in the presence of calcite and limestone. Since the granular layer through which the stormwater passes just prior to the sampling points is an extensive limestone bed a phosphate removal mechanism involving deposition as apatite can be postulated.

In addition to the results tabulated above, a number of VOC analyses (benzene, toluene, ethyl benzene, xylenes and MTBE) were also undertaken. However the concentrations in the pavement effluent were always below reporting limits (benzene, 10.0 µg/kg; toluene, 10.0 µg/kg; total xylenes, 10.0 µg/kg; ethyl benzene, 10.0 µg/kg; MTBE, 20.0 µg/kg), all below effluent limits derived from the Scottish Environmental Protection Agency (SEPA, 2010) environmental quality standards (benzene, 200 µg/l; toluene, 1000 µg/l; xylene, 600 µg/l; ethyl benzene, 400 µg/l; assuming a 1:20 dilution). In fact they were all even below typical limits for drinking water (EU limit for benzene 1.0 µg/l, US EPA for the other BTEX determinands 5, 1,00, 700 and 10,000 µg/l, respectively, and State of California for MTBE, 13.0 µg/l). Nevertheless, high concentrations of ethyl benzene were unexpectedly and regularly encountered within the channel (solids fraction, Table 2). Ethyl benzene was also detected on one occasion within the liquid extracted from the channel drains. The origin of the BTEX compounds in the

upstream channel collector is probably as a fraction from fuel losses from vehicles using the car park (possibly including indirect losses within lost lubricating oils). It is likely that these compounds were partitioned onto the solids within the channel and within any free product hydrocarbons floating on the surface. The relative volatility of these compounds would then be expected to lead to evaporative losses. Within the structure of the MPPS there are large areas of polyolefin within which partitioning onto the polymer might be expected and large surface area of stone which would provide a surface for biodegradation. In effect, the mechanisms available for attenuation of these pollutants are exactly the same in an MPPS as in a PPS. The main exceptions are the opportunity to remove that fraction trapped in the channel drain by way of the recommended maintenance regime of annual evacuation of the channels by gulley sucker is not available in a PPS and, in particular, the ability to respond to a major oil spillage before significant contamination of the sub surface has occurred. In a PPS, once the pollutants had reached the sub surface, any attempt to physically remove hydrocarbons trapped in the sub surface would involve significant works, possibly involving excavation of the full cross section below the spill.

MTBE was never detected in any part of the system. This oxygenated compound is added to gasoline as an anti-knock compound and is significantly more mobile than the BTEX fraction of the VOCs. In groundwater studies the MTBE is the first fraction to reach a monitoring site downstream. It is entirely feasible that the mobility of this compound allows it to escape very quickly from the MPPS, but it is also likely that there is a biological element to the mechanism (Squillace et al. 1997). Again this points the way to the need for further laboratory based studies.

In the case of toluene and xylenes, only single incidences of detectable concentrations were found in the liquids collected from the channel whilst large concentrations of these substituted benzenes were found within the solid fraction (Tables 2 and 3). Furthermore they were not detected in any of the effluents which suggested that these compounds were retained within the channel, largely by sorption onto the solids trapped there, and not released at concentrations which would cause concern.

4. Conclusions

The data generated in this survey indicate that the macro pervious pavement installed as a car park is producing effluent which is of a standard which is acceptable for direct release into a surface water receptor. Retention of significant amounts of hydrocarbons and heavy metals has been illustrated, although the complete mechanism of pollutant attenuation in the live car park environment has not been fully established to date. It has been demonstrated that the oil separating channel collector used in this installation is capable of retaining significant quantities of pollutants, and unlike a traditional pervious pavement does so such that these pollutants can be easily accessed for removal. Bearing in mind that the system is designed to deal with major spillages of oil in emergency situations the macro-pervious pavement

of the type investigated here offers significant advantages both in terms of major oil losses and day-to-day pollution arising from car parking. Additional investigation may also be warranted to understand whether pollutants are being biodegraded rather than simply being trapped. Finally, results from this investigation provide clear indication of the value of macro-pervious pavement systems equipped with channel drain based oil and silt retention devices and their potential for broad areas of the built environment is suggested.

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